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AUTHOR(S): W. O. Wray, J. Douglas Balcomb, Robert D. McFarland

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los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

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A SEMI-EMPIRICAL METHOD FOR ESTIMATING THE PERFORMANCE OF DIRECT GAIN PASSIVE SOLAR HEATED BUILDINGS

W. O. Wray, J. D. Balcomb and R. D. McFarland
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

The sunspot code for performance analysis of direct gain passive solar heated buildings is used to calculate the annual solar fraction for two representative designs in ten American cities. The two representative designs involve a single thermal storage mass configuration which is evaluated with and without night insulation. In both cases the solar aperture is double glazed. The results of the detailed thermal network calculations are then correlated using the monthly solar load ratio method which has already been successfully applied to the analysis of both active solar heated buildings and passive thermal storage wall systems. The method is based on a correlation between the monthly solar heating fraction and the monthly solar load ratio. The monthly solar load ratio is defined as the ratio of the monthly solar energy transmitted through the glazing aperture to the building's monthly thermal load.

The procedure using the monthly method for any location is discussed in detail. In addition, a table of annual performance results for 84 cities is presented, enabling the designer to bypass the monthly method for these locations.

1. Introduction

The solar load ratio method for estimating the performance of solar heated buildings was originally developed as a design tool for active systems.(1) Later the technique was modified slightly by Balcomb and McFarland(2) and applied to passive solar heated buildings of the thermal storage wall type. In this paper, the technique of Balcomb and McFarland, as described in Ref. 2, is extended to include direct gain passive solar heated buildings.

The solar load ratio method involves the use of a correlation between monthly solar heating fraction and monthly solar load ratio. The monthly solar load ratio is defined as the ratio of the solar radiation transmitted through the glazing of the solar aperture during a one month period to the total building heating load during the same one month period. Simulation results on which to base the correlation for direct gain buildings were obtained from a series of calculations performed with the PASOLE/SUNSPOT(3) thermal network code. SUNSPOT has been validated on the basis of experimental data from the direct gain test cell at the Los Alamos Solar Laboratory and although it is quite a simple model it is considered a reasonably accurate representation of actual direct gain buildings.

In the following sections we describe the procedure used to correlate the monthly solar heating fraction for direct gain buildings with the monthly solar load ratio. Limitations and accuracy of the resulting correlation are discussed. Finally a step-by-step procedure for estimating the annual performance of an arbitrarily located direct gain building on the basis of the solar load ratio correlation is presented.

2. The Reference Direct Gain Design

A single reference design is used in this study. It is, of course, desirable to have several reference designs available for analysis by the solar load ratio method and studies involving other configurations are therefore planned for the near future. At present, however, the performance of direct gain systems other than the reference design must be estimated by scaling the results based on parametric studies as will be discussed later.

The characteristics of the direct gain reference design are matched to corresponding characteristics of the previously reported solar load ratio analysis of thermal storage wall systems(4) wherever possible. For example, the direct gain design has a six inch thick layer of high density concrete distributed on the floor and north, east or west walls of the enclosure. The mass surface area is three times the glazing area. Thus the total volume of concrete thermal storage mass is equal to that available in an 18

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inch Trombe wall whose surface area equals the glazing area. The remaining characteristics of the reference direct gain design are:

- Thermal Storage: 45 Btu/°F-ft^2 of glazing
- Mass Distribution: 6 in. thick layer of concrete on floor and north, east or west walls. Mass surface area is three times the glazing area.
- Other Building Mass: Negligible
- Double Glazing: Normal solar transmittance = 0.747
- Air Temperature Range in Building: 65°F to 75°F
- Night Insulation: R9 when used. Insulation in place from 5 p.m. to 7 a.m.
- Mass-surface-to-room air conductance: 1.0 Btu/hr·ft^2·°F
- Storage Mass Properties:
  - thermal conductivity = 1.0 Btu/hr ft °F
  - heat capacity =30 Btu/ft^3 °F
- Glazing Orientation: Vertical and south facing
- Mass Surface Solar Absorptance: 0.8
- Ground Reflectance: 0.3
- Overhang: None

The above design is not as constrained as first appearances might indicate. Although the thickness and surface area of the thermal storage mass are fixed, the distribution of the mass along the interior surfaces of the enclosure is arbitrary except that the ceiling is excluded. During the course of validating the SUNSPOT model it was determined that the performance of direct gain enclosures is not very sensitive to variations of mass or solar radiation distribution within the enclosure. However, all non-massive surfaces are modeled as perfect reflectors representing the use of light colors on all light weight elements of the building shell. In order to account for the presence of furniture, rugs and other low thermal capacity objects in the direct gain enclosure, it is assumed that 20% of the transmitted solar flux was absorbed directly into the room air. This procedure synthesizes the absorption of solar radiation by objects which heat up rapidly due to their low heat capacity and subsequently lose thermal energy to the room air with very little lag time.

3. The Solar Load Ratio Correlation

A data base for the solar load ratio correlation was generated by performing a one year SUNSPOT calculation for the reference direct gain design (with and without night insulation) in each of ten American cities. The ten cities were selected on the basis of obtaining a variety of different types of climates. A list of the ten cities is presented in Table I as are the latitude, longitude, annual heating degree days and annual insolation at each site. The beginning date of the "typical year" historical weather file used for each city is also listed. The typical years were determined for each city on the basis of past work on active system simulation as the year which gives an annual performance closest to the average annual performance over a ten year period. Calculations in each city were run with and without night insulation for four different glazing area to building load ratios. Thus a total of 10 x 2 x 4 = 80 annual calculations were performed. The monthly data points obtained with and without night insulation are plotted in Figs. 1 and 2 respectively. In each figure, the monthly solar heating fraction is plotted as a function of the monthly solar load ratio. The grouping of the data points indicates that a correlation does exist and, as shown in Figs. 1 and 2, we have fit analytic curves to both sets of data. The functional relationship is given by:

$$SHF = a_1(SLR), \qquad SLR \leq R$$

$$SHF = a_2 - a_3 \, EXP\left|-a_4(SLR)\right| \quad , SLR > R$$

The coefficients selected are those which yield a least squares fit to annual solar heating fraction for the whole data set. The coefficients are given in Table II along with the standard deviation, σ, of the annual data.

The correspondence between annual solar heating fraction by the monthly solar load ratio method as compared with the hour-by-hour results is given in Figs. 3 and 4.

Table I

American Cities used in Solar Load Ratio Correlation

City	Latitude	Longitude	Annual Heating Degree Days	Annual Insolation (10^3Btu/ft^2)	Typical Year Start Date
Albuquerque	35.0	1.6	4253	688	7/1/62
Los Alamos	35.8	1.3	7350	518	9/1/72
Madison	43.0	-0.7	7838	513	7/1/61
Medford	42.3	2.9	5275	527	7/1/61
Boston	42.3	6.7	5535	444	7/1/57
Santa Maria	34.8	0.4	3065	649	7/1/56
Nashville	36.1	-3.3	3786	513	7/1/55
Charleston	32.8	5.0	2255	554	7/1/63
Bismark	46.8	10.8	8234	484	7/1/54
Lake Charles	30.1	3.2	1694	546	7/1/57

Table II

Coefficients for Solar Heating Fraction Correlation Function

	Direct Gain (DG)	Direct Gain with Night Insulation (DGNI)
R	0.100	0.600
a_1	0.6182	0.8865
a_2	1.0097	1.0028
a_3	1.0710	1.2646
a_4	1.2208	1 5467
σ	.025	.030

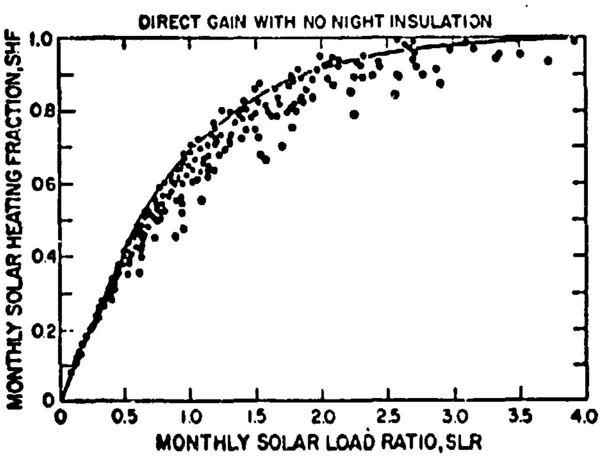

Fig. 1. Monthly Solar Heating Fraction vs Monthly Solar Load Ratio for reference direct gain design with no night insulation.

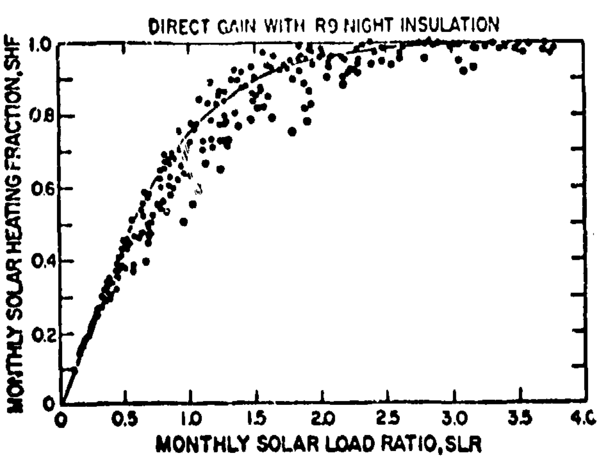

Fig. 2. Monthly solar heating fraction vs monthly solar load ratio for reference direct gain design with R9 night insulation.

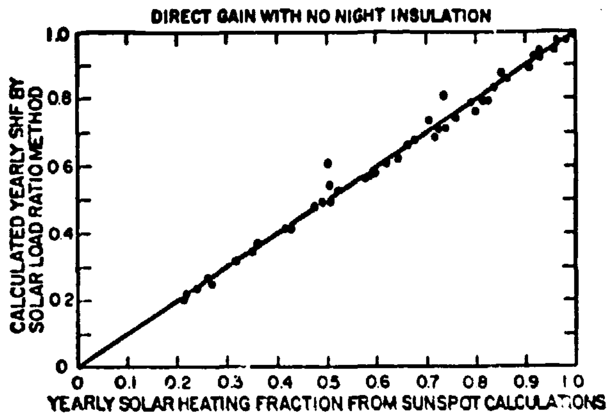

Fig. 3. Comparison of Annual Solar Heating fractions obtained from SUNSPOT calculations and by the solar load ratio method for the Reference Direct gain design with no night insulation.

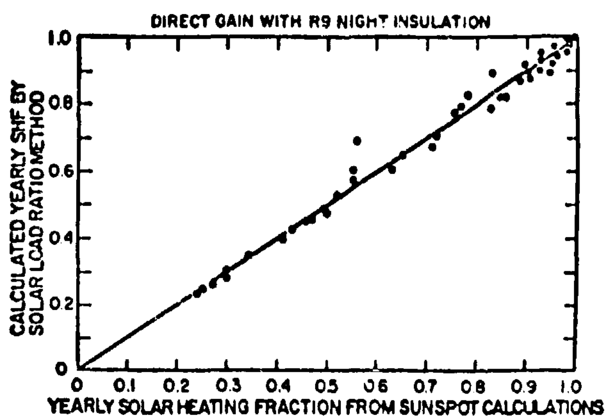

Fig. 4. Comparison of Annual Solar Heating Fraction obtained from SUNSPOT calculations and by the solar load ratio method for the reference direct gain design with R9 night insulation.

4. Estimating the Performance of Direct Gain Buildings

In this section we present a method for estimating the annual performance of direct gain solar buildings of the reference type at arbitrary locations. The only weather data required are total monthly insolation on a horizontal surface and monthly heating degree days. Extention of the results to non-reference designs is discussed in the following section.

Monthly Transmitted Solar Radiation

Step 1: Obtain the total monthly solar radiation on a horizontal surface, Q_H(Btu/ft^2), from weather data at the location of interest. Repeat for all 12 months.

Step 2: Calculate (L $-\delta$) for each month where
L = latitude (deg)
δ = 23.3° cos(30°M − 187°), solar declination at mid-month (M = month number, i.e. M = 1 for January)

Step 3: From Fig. 5, determine a value of Q_T/Q_H for each of the monthly values of (L-δ).
Then calculate

where Q_T is the monthly solar radiation transmitted through each square foot of vertical double glazing facing due south. (The data presented in Fig. 5 is the result of hour by hour simulations in 21 U.S. cities. The Boes correlation[5] was used to determine hourly direct normal and diffuse solar radiation from hourly total horizontal radiation). The analytic form of the function presented in Fig. 5 is:

$$\frac{Q_T}{Q_H} = .266 - .00251\ (L-\delta) + .000308(L-\delta)^2 \qquad (2)$$

The standard deviation is 0.060.

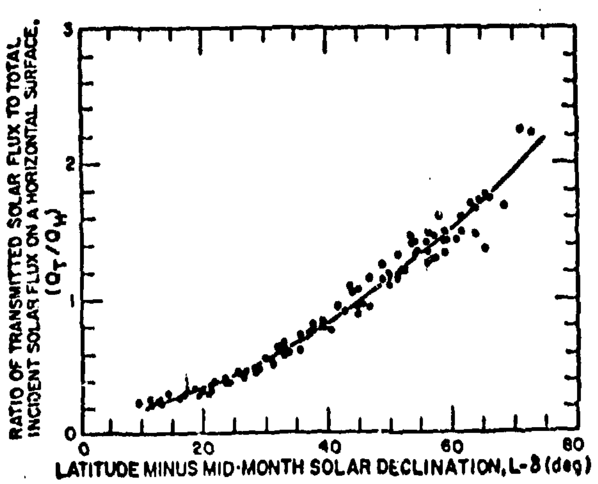

Fig. 5. Ratio of solar flux transmitted through double glazing to solar flux incident on horizontal surface vs latitude minus mid-month solar declination.

Step 4: The relationship represented in Equation (2) is based on an assumed ground reflectance of 0.3. In some cases a designer may wish to use a horizontal specular reflector on the ground in front of the solar aperture. If the reflector is equal in area to the glazing aperture and has a reflectance of 0.8, the monthly transmitted solar radiation is enhanced as illustrated in Fig. 6. The enhanced monthly transmitted solar radiation is given by

$$Q_T = Q_T \cdot EF$$

where EF is the enchancement factor and Q_T is the transmitted solar radiation obtained in Step 3 above. The correlation in Fig. 6 was obtained from hour by hour simulations in ten American cities. The standard deviation is 0.0197. The analytic form of the function in Fig. 6 is:

$$EF = 1.008 - .0179(L-\delta) + .00192\ (L-\delta)^2 - 4.03 \times 10^{-5}(L-\delta)^3 + 2.45 \times 10^{-7}(L-\delta)^4 \qquad (3)$$

Q_T is the desired monthly transmitted solar radiation.

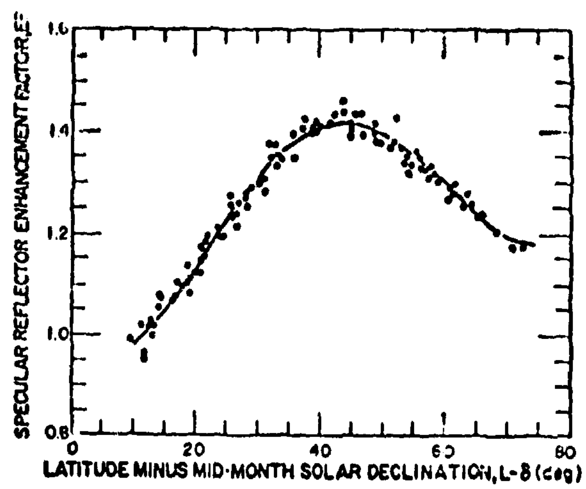

Fig. 6. Specular reflector enhancement factor vs latitude minus mid-month solar declination.

Monthly Thermal Load

Step 1: Calculate the building loss coefficient (BLC) in Btu/degree-day. The BLC is the sum of the building skin conductance (including the south facing glazing) and the infiltration.

Step 2: Determine the monthly heating degree days, DD, from weather data at the site of interest.

Step 3: Determine the monthly thermal load, MTL, by taking the product of the building loss coefficient and the monthly heating degree day values.

$$MTL = BLC \cdot DD$$

Monthly Solar Load Ratio

The monthly solar load ratio is

$$SLR = Q_T/MTL$$

Monthly Solar Heating Fraction

Each previously calculated monthly solar load ratio corresponds to a unique monthly solar heating fraction, SHF, which can be obtained from the solid lines graphed in Figs. 1 and 2 for designs with and without night insulation, respectively.

Monthly Auxiliary Energy Required

The auxiliary heating energy, AUX, required each month is calculated as follows:

$$AUX = (1-SHF) \cdot BLC \cdot DD$$

Annual Auxiliary Energy Required

Simply sum the monthly AUX's to get the annual total.

$$\text{ANNUAL AUX} = \sum_{i=1}^{12} AUX_i$$

Annual Solar Heating Fraction

Sum monthly heating degree days to get ANNUAL DD and evaluate the annual solar fraction as follows:

5. Variations from the Reference Designs

In the near future solar load ratio curves will be generated for several additional direct gain configurations in order to extend the applicability of the solar load ratio method. In the meantime, the performance of non-reference configurations must be approximated by scaling annual solar fractions obtained for the reference design on the basis of detailed sensitivity study results. The variation of annual solar heating fraction as a function of number of glazings, resistance of night insulation, thickness of thermal storage mass, surface area of thermal storage mass, and allowable room air temperature swing has been determined by performing an extensive matrix of SUNSPOT calculations. The results are reported in another paper in these proceedings.[6] From the calculated results presented in Reference 6 it is possible to determine the fractional change in annual solar heating fraction which results from a selected design departure from the reference system. The annual solar heating fraction obtained by the solar load ratio method can be multiplied by the appropriate fractional change in order to determine the performance of the configuration of interest to the designer. Application of this approximation involves the implicit assumption that fractional variations of the annual solar heating fraction due to changes in a single design parameter are insensitive to the values of the remaining design parameters. This implicit assumption is of course not rigorously correct but use of the suggested scaling correction is better than using no correction at all for off-reference configurations.

6. Tabular Solution for Annual Solar Heating Fraction in 84 U.S. and Canadian Cities

A variation of the solar load ratio method described in section 4 has been used to calculate annual solar heating fractions for the reference direct gain designs in 84 U.S. and Canadian cities and the results are presented in Table III. A designer interested in a building site located in one of the cities included in Table III need not perform the month by month calculations required by the solar load ratio method. Instead, the following much simpler procedure may be followed:

Step 1: Calculate the building loss coefficient (BLC) in Btu/degree-day. This is the sum of the building skin conductance (excluding the south facing glazing) and the infiltration load. Internal heat sources may be subtracted from the building loss coefficient. IMPORTANT: Remember that when using Table III the calculated building loss coefficient should not include the south facing glazing of the solar aperture.

Step 2: Calculate the building load collector ratio (LCR) defined as follows:

$$LCR = \frac{BLC}{\text{Solar Collection Area } (ft_g^2)}$$

Step 3: Locate the city and reference design of interest in Table III. The symbol DG refers to the direct gain design and DGNI is the direct gain design with night insulation. The load collector ratios required to achieve the indicated solar heating fractions, which range from 0.1 to 0.9, appear beneath the solar heating fractions. It will usually be necessary to interpolate in the table in order to determine the correct solar heating fraction.

Step 4: The annual auxiliary energy required by the building is given by:

$$\text{ANNUAL AUX} = (1-SHF) \cdot (\text{ANNUAL DD}) \cdot (BLC)$$

where, again, the building loss coefficient does not include the solar aperture.

TABLE III: Heating-LOAD/COLLECTOR-AREA RATIO FOR GIVEN SOLAR FRACTIONS
Heating-Load in Btu/DD; Area in Sq. Ft.

Page, AZ — 6632 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	217.0	110.5	64.6	39.1	22.4	0.0	0.0	0.0	0.0
LCR(DGNI)	339.0	156.1	97.6	68.6	51.3	38.9	28.7	19.9	11.6

Phoenix, AZ — 1765 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	724.5	396.7	256.0	177.7	127.6	92.5	66.0	44.7	26.0
LCR(DGNI)	959.8	452.8	289.2	209.3	158.9	123.7	95.8	71.2	48.1

Tucson, AZ (State Univ.) — 1800 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	724.7	394.6	253.6	175.9	126.3	91.6	65.6	44.6	26.3
LCR(DGNI)	974.3	451.0	286.0	206.3	157.0	123.1	95.4	71.2	48.4

Little Rock, AR — 3219 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	269.4	140.0	84.0	53.1	33.3	19.3	0.0	0.0	0.0
LCR(DGNI)	405.1	188.6	116.2	82.1	61.2	46.7	34.8	24.6	15.0

Davis, CA — 2502 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	486.2	249.5	154.6	102.2	69.3	46.4	29.4	15.5	0.0
LCR(DGNI)	664.7	307.2	190.7	133.8	96.3	73.5	55.2	39.3	24.5

El Centro, CA — 1458 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	1211.3	662.5	428.2	298.2	215.8	158.7	116.[illegible]	82.2	52.5
LCR(DGNI)	1578.6	742.0	464.8	331.4	251.3	197.1	153.3	115.3	79.7

Fresno, CA — 2492 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	476.9	242.9	149.4	97.9	65.5	43.3	26.7	13.0	0.0
LCR(DGNI)	642.3	303.1	186.2	129.5	94.6	70.2	52.5	37.1	22.9

Inyokern, CA (China Lake) — 3528 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	528.6	280.1	176.0	118.5	82.2	57.0	38.3	23.5	0.0
LCR(DGNI)	727.4	338.6	210.7	147.8	110.6	84.9	64.7	47.2	31.0

Los Angeles, CA — 2061 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	892.7	489.1	314.2	216.8	155.1	112.4	80.9	56.0	34.6
LCR(DGNI)	1177.7	563.1	350.1	247.0	186.1	145.6	112.7	84.4	58.1

Riverside, CA — 1803 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	895.5	488.1	314.8	218.7	157.6	115.1	83.4	58.0	35.7
LCR(DGNI)	1182.8	551.7	348.2	249.4	190.2	149.0	115.7	86.8	59.5

Boise, ID — 5809 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	205.2	98.6	53.5	27.4	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	328.2	151.1	91.9	61.7	43.6	31.0	21.7	13.6	0.0

Argonne Nat. Lab., Lemont, IL — 6155 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	124.3	54.2	21.2	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	231.0	103.9	62.6	42.7	30.8	22.3	15.3	9.2	0.0

Indianapolis, IN — 5699 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	142.6	64.7	30.2	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	254.7	114.6	68.7	46.8	33.8	24.5	17.0	10.6	0.0

Ames, IA (State Univ.) — 6588 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	119.0	51.3	16.7	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	223.7	101.1	61.0	41.6	29.9	21.5	14.7	8.7	0.0

Dodge City, KS — 4986 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	245.0	177.7	76.8	48.4	30.0	16.5	0.0	0.0	0.0
LCR(DGNI)	368.1	174.0	109.1	77.0	57.8	44.3	32.9	23.2	14.1

Manhattan, KS — 5182 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	177.6	87.4	48.2	25.8	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	290.9	134.7	82.8	57.5	42.4	31.7	22.8	15.3	8.2

Lexington, KY — 4683 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	150.7	70.8	35.7	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	260.8	119.4	72.4	49.7	36.2	26.6	18.8	12.1	0.0

Lake Charles, LA — 1459 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	601.4	325.1	207.7	142.9	101.6	72.8	51.1	33.7	18.3
LCR(DGNI)	817.4	377.3	239.2	172.9	131.5	102.3	79.0	58.5	39.2

Shreveport, LA — 2184 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	405.6	218.0	136.9	92.0	63.6	43.8	28.9	16.7	0.0
LCR(DGNI)	573.3	266.3	167.4	120.3	91.2	71.2	54.4	35.8	26.2

Caribou, ME — 9767 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	76.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	175.4	78.1	46.9	31.1	21.2	14.2	8.3	0.0	0.0

Santa Maria, CA — 2967 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	660.7	372.7	243.7	170.2	122.4	88.7	63.2	42.7	24.7
LCR(DGNI)	853.2	426.6	278.5	200.4	152.7	119.8	92.5	68.9	46.6

Boulder, CO — 5509 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	211.8	109.4	64.8	39.9	23.5	0.0	0.0	0.0	0.0
LCR(DGNI)	327.2	152.8	96.6	69.0	52.0	39.8	29.5	20.7	12.3

Granby, CO — 10802 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	90.2	39.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	169.6	84.6	54.6	38.8	28.5	20.8	14.3	8.6	0.0

Grand Junction, CO — 5641 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	222.1	114.0	67.3	41.0	23.8	0.0	0.0	0.0	0.0
LCR(DGNI)	341.4	160.6	100.6	70.7	52.6	39.7	29.2	20.2	11.8

Washington, DC, Silver Hill, MD — 4224 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	225.5	114.6	66.8	40.2	22.9	0.0	0.0	0.0	0.0
LCR(DGNI)	351.5	162.3	100.4	70.1	51.8	39.1	28.7	19.8	11.5

Apalachicola, FL — 1308 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	818.2	446.4	287.3	199.4	143.5	104.5	75.3	52.0	31.4
LCR(DGNI)	1093.5	505.9	321.2	229.9	175.0	137.4	106.5	79.7	54.5

Gainesville, FL — 1239 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	857.7	466.8	301.1	209.8	151.6	111.0	80.5	56.0	34.3
LCR(DGNI)	1146.3	524.3	334.5	240.5	183.9	144.6	112.5	84.4	57.8

Tallahassee, FL (State Univ.) — 1485 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	701.7	392.9	245.1	169.0	121.0	87.6	62.6	42.5	25.0
LCR(DGNI)	952.4	439.3	276.4	198.7	151.1	118.8	92.0	68.7	46.8

Tampa, FL — 683 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	1403.0	802.6	533.8	380.6	281.0	210.4	156.9	113.6	75.1
LCR(DGNI)	1742.7	871.4	570.1	415.6	321.8	255.7	200.7	152.7	107.1

Atlanta, GA — 2961 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	342.3	179.5	110.0	71.8	47.7	30.8	18.1	0.0	0.0
LCR(DGNI)	500.5	230.0	142.3	100.2	75.0	57.7	43.4	11.2	19.8

Portland, ME — 7511 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	132.2	60.0	27.4	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	238.5	108.0	66.1	45.4	32.9	24.0	16.7	10.3	0.0

Boston, MA — 5634 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	141.4	65.2	32.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	250.3	113.2	69.0	47.8	34.8	25.6	18.0	11.4	0.0

East Lansing, MI — 6909 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	111.0	44.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	218.5	96.8	57.6	38.8	27.6	19.5	13.0	7.2	0.0

Sault Ste. Marie, MI — 9048 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	90.0	25.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	194.6	85.9	50.8	33.4	22.6	15.1	8.9	0.0	0.0

Saint Cloud, MN — 8879 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	93.6	31.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	198.1	87.5	52.2	34.7	24.0	16.4	10.3	0.0	0.0

Columbia, MO — 5046 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	188.9	92.5	51.1	27.7	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	309.0	141.2	86.0	59.4	43.5	32.4	23.3	15.6	8.3

Glasgow, MT — 8996 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	179.0	87.1	47.0	23.3	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	295.0	136.5	83.6	57.2	41.2	29.9	21.1	13.6	0.0

Great Falls, MT — 7750 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	146.2	67.5	32.1	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	255.7	117.6	71.9	48.6	34.3	24.3	16.5	9.7	0.0

Lincoln, NB — 5864 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	189.9	93.0	51.4	28.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	310.6	141.8	86.3	59.4	43.7	32.5	23.5	15.8	8.5

Ely, NV — 7733 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	191.1	97.6	56.9	33.9	18.1	0.0	0.0	0.0	0.0
LCR(DGNI)	299.6	141.4	89.6	63.6	47.8	36.3	26.7	18.4	10.6

Las Vegas, NV 2709 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	513.9	278.1	175.8	119.1	83.0	58.1	39.5	24.6	0.0
LCR(DGNI)	708.4	333.4	208.6	148.4	111.7	86.2	66.0	48.4	31.9

Reno, NV 6332 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	207.8	105.7	61.1	35.9	18.9	0.0	0.0	0.0	0.0
LCR(DGNI)	325.2	152.4	95.4	66.8	49.1	36.5	26.6	18.0	9.8

Seabrook, NJ 4812 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	170.2	82.4	44.5	27.3	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	283.9	130.1	79.5	55.2	40.4	30.1	21.5	14.2	0.0

Albuquerque, NM 4348 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	321.9	173.5	108.2	71.6	48.1	31.6	19.0	0.0	0.0
LCR(DGNI)	457.4	220.4	139.8	99.5	75.5	58.4	44.2	31.9	20.4

Ithaca, NY 6914 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	81.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	189.2	80.9	47.0	31.0	21.3	14.3	8.5	0.0	0.0

New York, NY (Central Park) 4871 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	158.6	76.0	39.9	17.9	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	269.4	123.4	75.5	52.4	38.3	28.4	20.2	13.2	0.0

Sayville, NY 4811 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	182.3	90.8	51.0	28.3	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	294.5	137.3	84.9	59.5	43.9	33.0	23.9	16.1	8.8

Schenectady, NY 6650 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	78.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	177.9	79.0	47.1	31.6	22.0	15.1	9.3	0.0	0.0

Greensboro, NC 3805 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	264.0	136.6	81.9	51.7	32.5	18.6	0.0	0.0	0.0
LCR(DGNI)	398.9	184.1	114.4	80.5	60.2	46.0	34.3	24.2	14.8

Hatteras, NC 2612 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	463.4	249.1	156.3	105.1	72.7	50.2	33.5	20.0	0.0
LCR(DGNI)	651.9	301.5	189.9	133.7	100.5	77.9	59.4	43.4	28.4

Newport, RI (Eppley Lab.) 5804 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	157.2	75.6	40.1	18.9	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	267.2	121.9	75.0	52.3	38.7	28.[illegible]	20.8	13.8	0.0

Charleston, SC 2033 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	507.2	275.5	174.2	118.2	82.8	58.2	40.0	25.4	0.0
LCR(DGNI)	703.2	329.0	205.1	146.5	111.0	86.7	66.6	49.2	32.9

Rapid City, SD 7345 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	159.8	77.3	40.9	18.7	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	269.5	124.5	76.8	53.0	38.8	28.6	20.3	13.2	0.0

Nashville, TN 3578 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	244.0	122.0	70.6	42.5	24.5	0.0	0.0	0.0	0.0
LCR(DGNI)	384.1	172.4	104.2	72.3	53.2	40.2	29.5	20.4	11.9

Oak Ridge TN 3817 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	221.8	110.9	63.6	37.5	20.4	0.0	0.0	0.0	0.0
LCR(DGNI)	351.8	159.8	97.4	67.5	49.9	37.6	27.5	18.9	10.8

Brownsville, TX 600 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	1308.7	740.0	492.6	350.8	258.3	192.4	142.2	101.4	65.0
LCR(DGNI)	1607.2	803.6	533.0	390.2	299.8	234.6	183.2	137.7	94.7

El Paso TX 2700 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	505.2	278.1	177.4	120.3	84.9	59.7	41.0	25.9	0.0
LCR(DGNI)	688.3	331.4	209.3	149.9	113.7	88.0	67.6	49.8	33.0

Fort Worth, TX 2405 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	424.1	230.6	145.7	98.4	68.2	47.2	31.4	18.5	0.0
LCR(DGNI)	590.3	279.9	177.0	127.1	96.1	74.6	57.1	41.8	27.4

Midland, TX (Sloan Field) 2591 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	449.4	246.2	156.3	105.9	73.8	51.3	34.6	21.1	0.0
LCR(DGNI)	616.0	297.5	187.6	134.4	101.8	79.1	60.6	44.5	29.4

San Antonio, TX 1546 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	644.3	350.8	224.4	154.5	110.2	79.3	56.2	37.6	21.3
LCR(DGNI)	872.9	405.5	255.7	184.4	140.1	109.5	84.7	63.1	44.6

Raleigh, NC 3393 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	290.7	151.7	92.1	59.3	38.4	23.6	11.9	0.0	0.0
LCR(DGNI)	431.8	200.0	124.2	87.4	65.7	50.6	37.9	27.1	17.0

Bismark, ND 8851 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	120.3	43.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	219.2	97.1	57.6	38.1	26.5	18.4	11.8	5.9	0.0

Cleveland, OH 6351 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	94.3	30.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	203.7	87.8	51.3	34.0	23.7	16.4	10.3	0.0	0.0

Columbus, OH (State Univ.) 5211 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	121.7	52.5	17.4	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	228.0	102.8	61.9	42.2	30.0	21.4	14.5	8.4	0.0

Put-in-Bay, OH (Stone Lab.) 5796 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	95.3	28.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	207.6	88.8	51.6	34.1	22.8	15.1	8.8	0.0	0.0

Oklahoma City, OK 3725 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	276.2	144.2	87.2	55.7	35.6	21.3	0.0	0.0	0.0
LCR(DGNI)	411.7	191.7	119.4	84.3	63.1	48.4	36.2	25.7	15.9

Astoria, OR 5186 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	236.9	117.3	67.3	38.5	17.8	0.0	0.0	0.0	0.0
LCR(DGNI)	349.7	169.6	105.4	72.1	51.0	36.2	25.0	15.7	0.0

Corvallis, OR (State College) 4726 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	252.5	118.7	66.5	37.5	17.3	0.0	0.0	0.0	0.0
LCR(DGNI)	389.7	172.4	104.6	70.8	50.1	35.8	25.1	16.0	0.0

Medford, OR 5008 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	201.9	94.5	50.6	24.8	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	324.0	146.7	89.6	60.4	42.4	29.8	20.4	12.4	0.0

State College, PA 5934 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	120.5	52.1	17.6	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	225.9	102.2	61.6	41.9	30.1	21.6	14.7	8.7	0.0

Flaming Gorge, UT 6929 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	189.7	96.6	55.6	32.4	16.1	0.0	0.0	0.0	0.0
LCR(DGNI)	299.7	141.3	89.0	62.7	46.7	35.2	25.7	17.6	9.9

Salt Lake City, UT 6052 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	212.4	106.5	60.7	34.9	17.2	0.0	0.0	0.0	0.0
LCR(DGNI)	336.8	155.5	96.0	66.3	48.3	35.6	25.7	17.2	9.2

Burlington, VT 8269 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	64.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	169.1	72.4	42.4	27.9	19.2	12.7	7.1	0.0	0.0

Pullman, WA 5542 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	194.0	89.3	45.8	18.2	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	316.3	143.3	86.3	57.1	39.5	27.4	18.5	10.9	0.0

Richland, WA 5941 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	195.0	87.2	42.9	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	320.5	143.5	85.3	55.3	37.5	25.6	17.0	9.6	0.0

Seattle, WA (Univ. of Wash.) 4424 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	243.7	109.0	57.4	28.1	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	380.2	167.0	98.8	64.9	44.3	30.4	20.4	12.0	0.0

Spokane, WA 6655 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	156.6	67.2	27.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	276.5	123.0	72.6	47.0	31.7	21.3	13.6	6.8	0.0

Madison, WI 7863 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	104.5	40.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	212.2	93.3	55.3	37.1	26.2	18.4	12.0	6.4	0.0

Lander, WY 7870 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	182.8	92.8	53.1	30.2	13.3	0.0	0.0	0.0	0.0
LCR(DGNI)	289.5	137.8	87.0	61.2	45.3	33.9	24.6	16.6	9.1

Laramie, WY (State Univ.) 7381 DD

SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	171.9	86.1	48.8	27.4	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	277.7	130.1	81.8	57.9	43.6	32.9	24.1	16.5	9.[illegible]

Edmonton, Alberta, Canada					10268 DD				
SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	79.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	192.9	83.6	46.1	26.8	15.2	6.6	0.0	0.0	0.0

Toronto, Canada					6827 DD				
SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	102.5	39.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	207.7	92.1	55.1	37.0	26.1	18.3	11.9	6.2	0.0

Ottawa, ONT., Canada					8735 DD				
SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	77.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	184.8	78.9	46.2	30.1	20.4	13.5	7.7	0.0	0.0

Winnipeg, MAN., Canada					10679 DD				
SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR(DG)	56.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR(DGNI)	163.5	70.9	40.6	25.0	15.5	8.6	0.0	0.0	0.0

7. Conclusion

The information and techniques presented in this paper, when combined with the results of the sensitivity study reported in Reference 6, are sufficient to provide an estimate of the annual performance of most direct gain designs at any building site in the United States or Canada. Solar load ratio correlations for additional direct gain designs will be developed in the near future in order to minimize the amount of scaling (based on sensitivity calculations) required to estimate building performance.

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